A look beyond ΛCDM

Workshop on Tensions in Cosmology

22nd Hellenic School and Workshops on Elementary Particle Physics and Gravity,

Corfu, Greece, 7/12 September 2022

William Giarè

GGI Galileo Galilei Institute for Theoretical Physics

CENTRO NAZIONALE INFN DI STUDI AVANZATI

william.giare@uniroma1.it William Giarè www.williamgiare.com github.com/WilliamGiare 0000-0002-4012-9285

Tensions and Anomalies in Cosmology

Hubble Parameter (H_0)

- Tension between **CMB** and local measurements

Matter clustering (Ω_m / σ_8 / S_8)

- Tension between **CMB** and weak leasing surveys

Lensing Amplitude (A_{LENS}) and Curvature (Ω_K)

- Moderate **Planck** preference for higher lensing amplitude and closed Universe

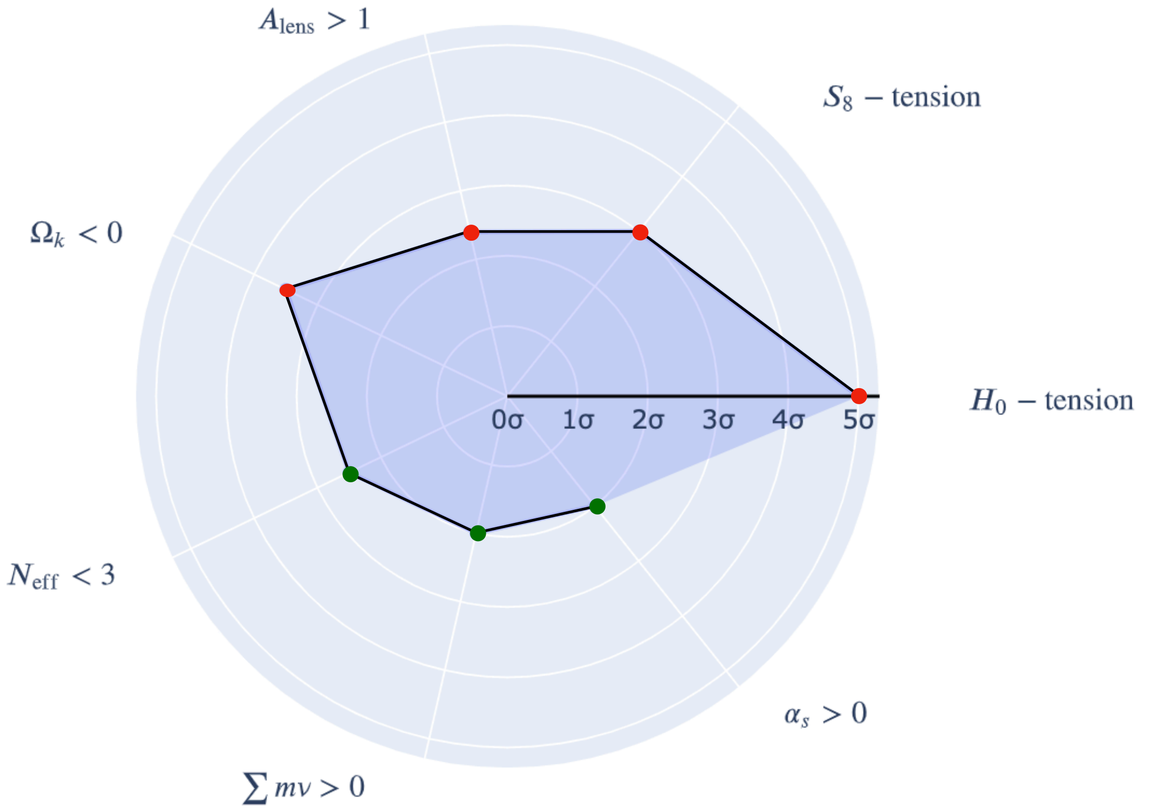
Neutrinos (M_V) and Early Universe Radiation (N_{eff})

- Mild **ACT** preference for the neutrino mass and $N_{eff}<3$

Running(s) of inflationary spectral index (α_s)

- Slight **ACT** preference for a running of the spectral index $\alpha_s > 0$

Some intriguing cosmological tensions and anomalies



Directions in beyond ΛCDM Cosmology

1

Parametric Extensions to ΛCDM

We can relax some assumptions of ΛCDM and introduce additional parameters

$$\Lambda\,\mathrm{CDM} + \sum_{\mathrm{i}} \mathrm{p_i}$$

$$p_i \in \{\Omega_k\,, dn_{\mathrm{s}}/d\log k\,, N_{\mathrm{eff}}\,, \sum m_\nu\,, \ldots\}$$

or even different parameterizations for the dark sector

$$\mathrm{X\,CDM}$$

$$\mathrm{X} \in \{\Lambda\,, \mathrm{w_0}\,, \mathrm{w_0 w_a}, \ldots\}$$

2

Extensions to Fundamental Physics

More precise observations will offer us the possibility to use Cosmology as a laboratory to test fundamental Physics

Extensions to GR

Modified gravity theories able to capture the underling phenomenology of the early and late time Universe.

Extensions to SM

extensions to the SM with additional species/ DM candidates

EXTENDED MODELS

$$\underset{X \in \{\Lambda, w\}}{X\,\mathrm{CDM} + \sum_i p_i} \in \{\Omega_k, N_{\mathrm{eff}}, \sum m_\nu, dn_s/d\log k\}$$

Curvature (Ω_K)

We explore curved background geometries parametrized by the curvature density parameter

Neutrinos (M_ν) and Early Universe Radiation (N_{eff})

we consider neutrinos as massive particles, as robustly indicated by oscillation experiments

we change the amount of radiation in the early Universe by the effective number of relativistic particles

Dark Energy (w) and Inflation (α_s)

We relax the assumption $w = w_\Lambda \equiv -1$ for Dark Energy equation of state

We relax we relax the assumption of scale-invariant primordial perturbations by introducing a running of the spectral index α_s

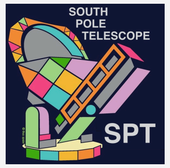
DATA

Planck 2018 (TT TE EE)

temperature and polarization likelihood which also includes low multipole data (L < 30)

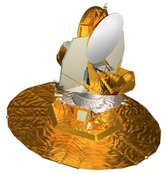
Atacama Cosmology Telescope (ACT)

DR4 likelihood and a Gaussian prior on $\tau = 0.065 \pm 0.015$



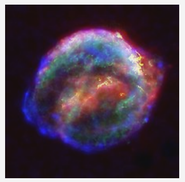
South Pole Telescope (SPT)

TE measurements and a Gaussian prior $\tau = 0.065 \pm 0.015$



WMAP

9-yrs observations, Always Combined with ACT or SPT



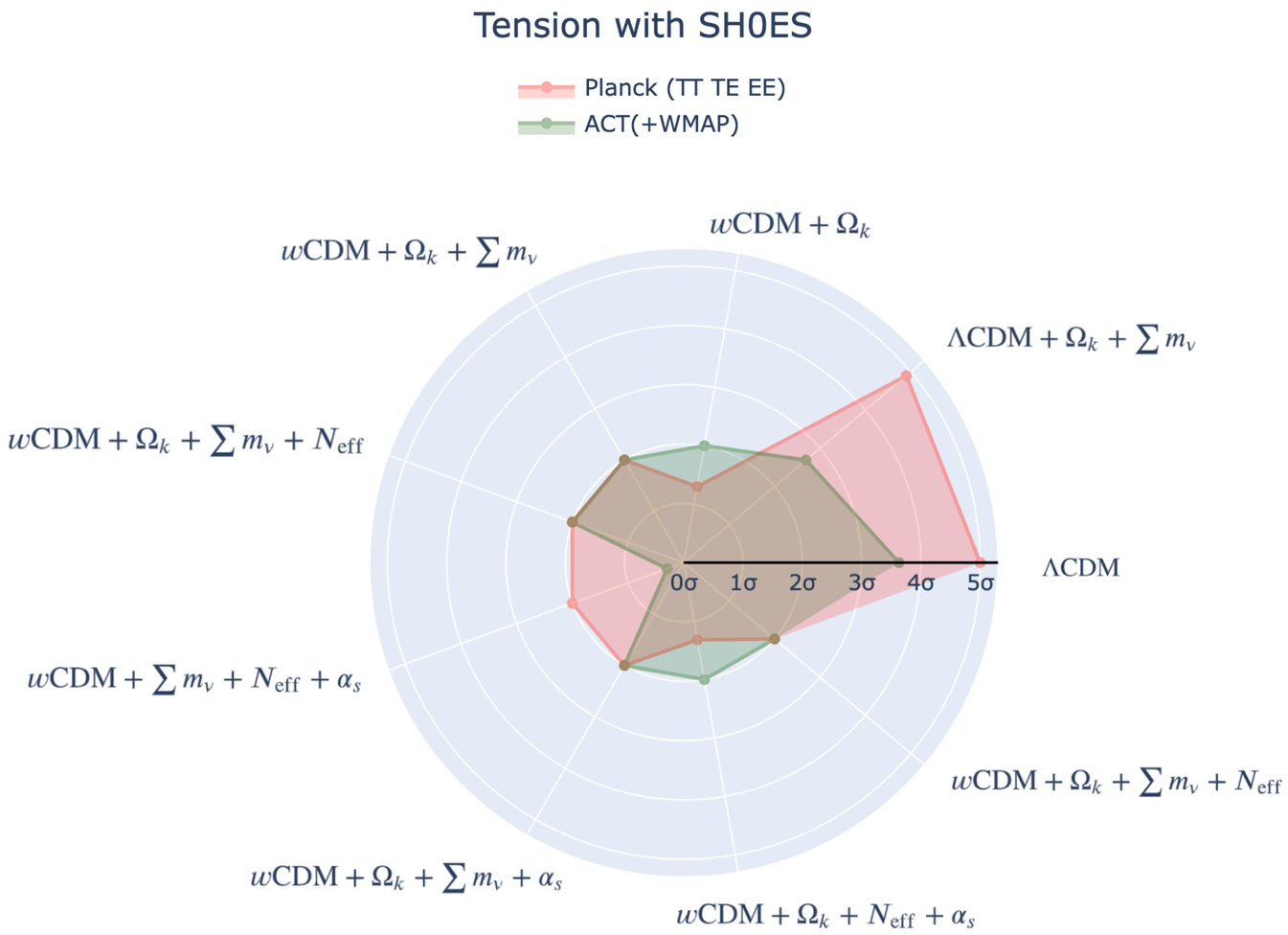
CMB-Independent dataset

we test the robustness of results by adding CMB-independent astrophysical observations such as **BAO** and **SNIa** distance moduli measurements from the **Pantheon** sample

General Results

In collaboration with:
E. Di Valentino, A. Melchiorri, J. Silk

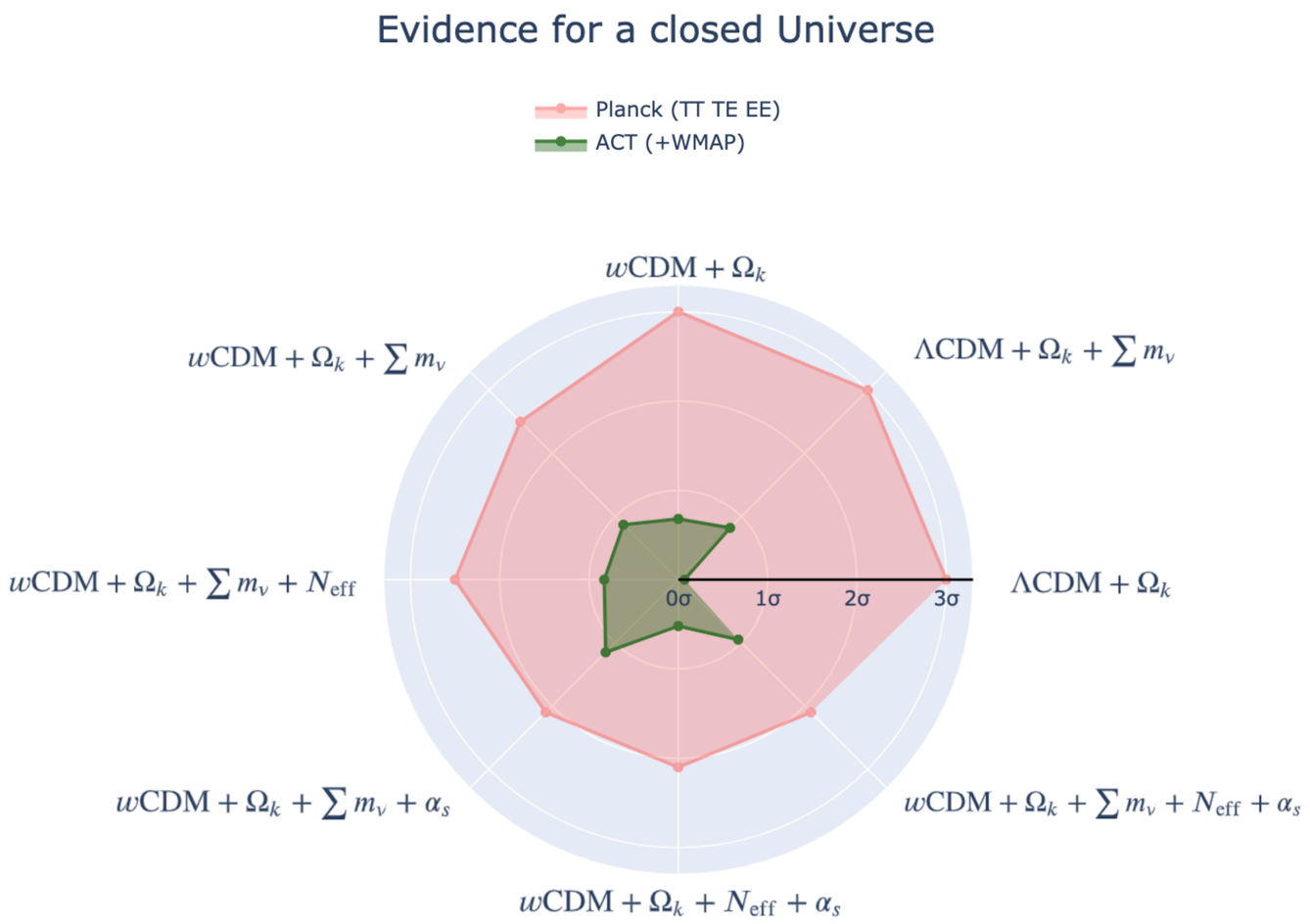
Background parameters



Expansion Rate (H_0)

- In extended cosmologies, H_0 is often poorly constrained by the CMB data and tension is alleviated due to the large error-bars
- when the different CMB observations are combined with astrophysical datasets the errors are typically reduced and the tension increased.
- **Not a solution,** but the values of H_0 inferred from the CMB data is largely sensitive to the underlying cosmological model

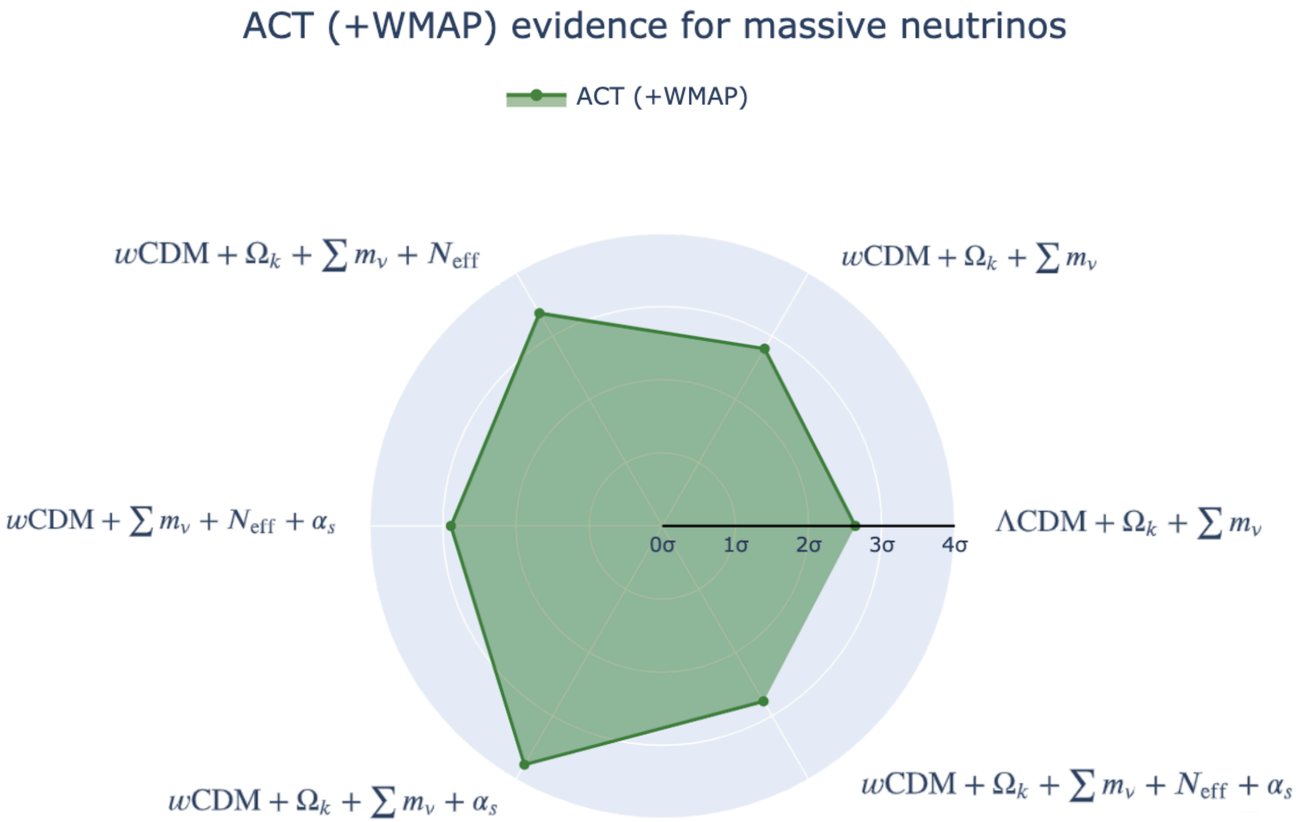
Background parameters



Curvature (Ω_K)

- The Planck preference for a closed Universe is not reduced in extended cosmologies.
- Both ACT and SPT data (combined with WMAP), remain consistent with spatial flatness.
- This may lead weight to the hypothesis of some unaccounted for systematic in the Planck data (?!)

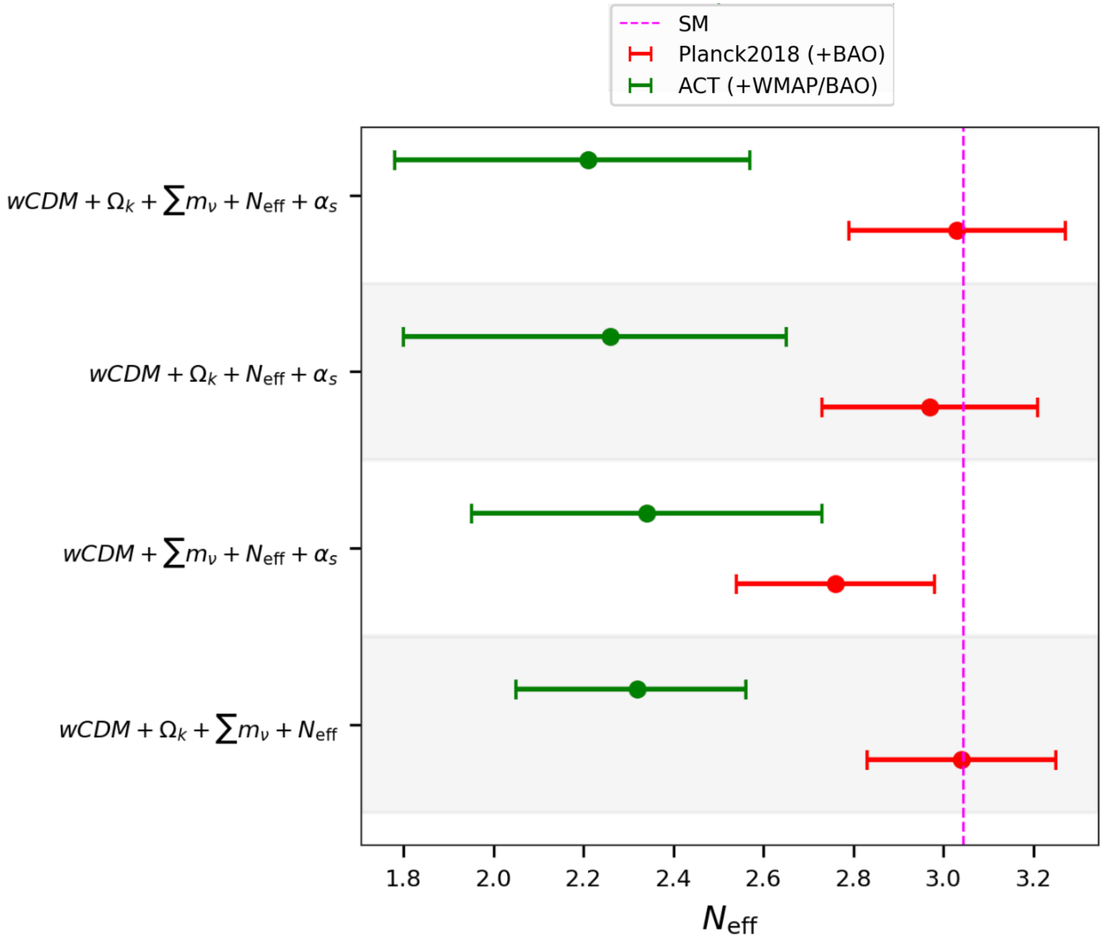
Neutrinos and Early Universe Radiation



Neutrinos (M_ν)

- Planck and SPT (+WMAP) are generally consistent with massless neutrinos within about one standard deviation.
- For both these datasets including astrophysical observations only gives more constraining mass limits.
- ACT (combined with WMAP) always shows a moderate-to-strong preference for massive neutrinos (2.5σ – 4σ)
- When we add BAO and Pantheon, this evidence, although slightly reduced, can be still observed, producing an interesting indication for massive neutrinos.

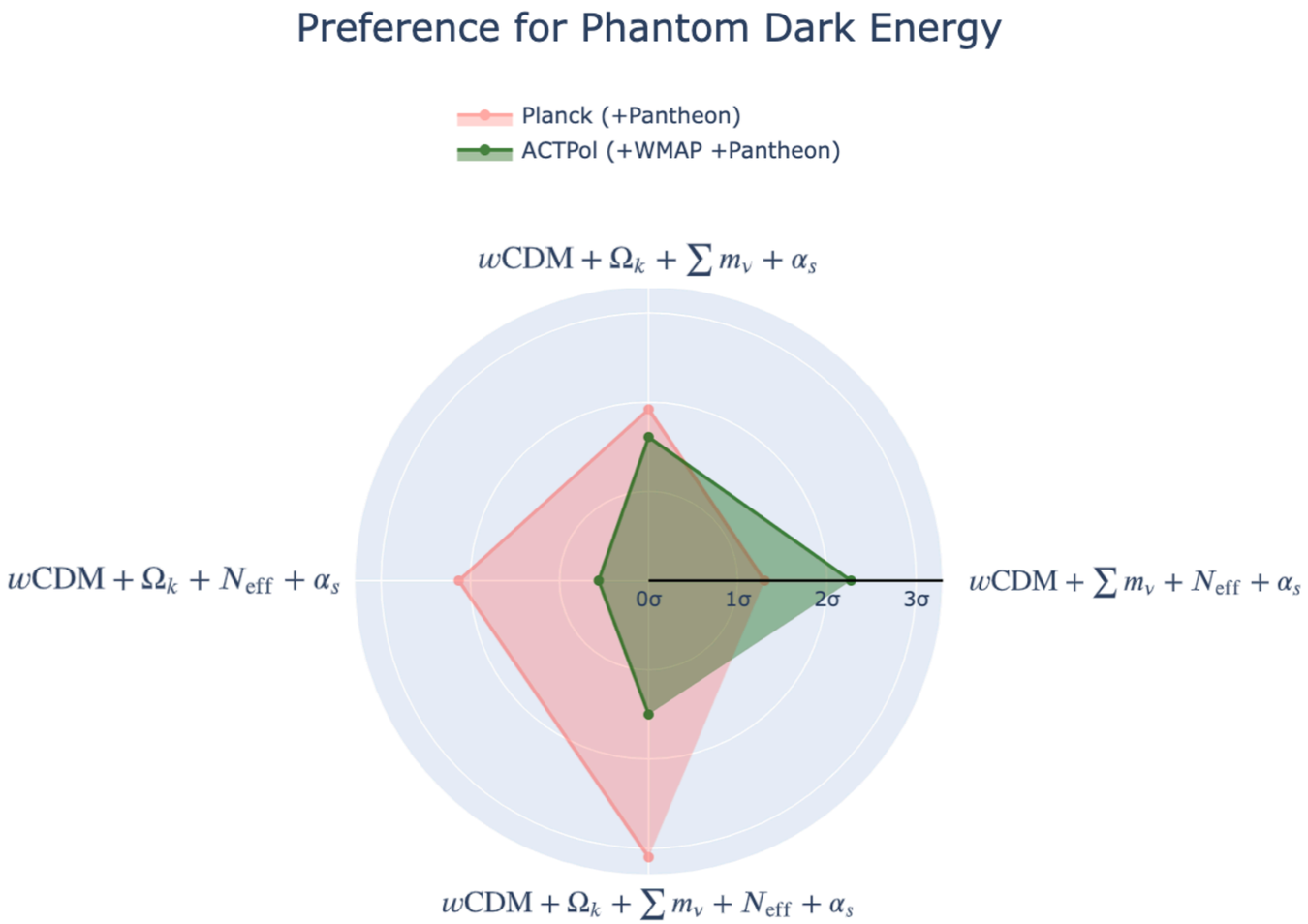
Neutrinos and Early Universe Radiation



Radiation Energy Density ($N_{\rm eff}$)

- Planck and SPT (as well as their combination with BAO and Pantheon) are in good agreement with the value predicted by Standard Model (SM)
- ACT shows a preference for a smaller amount of radiation in the early Universe, with a statistical significance that changes between 1.8σ and 3σ
- This indication remains including astrophysical observations

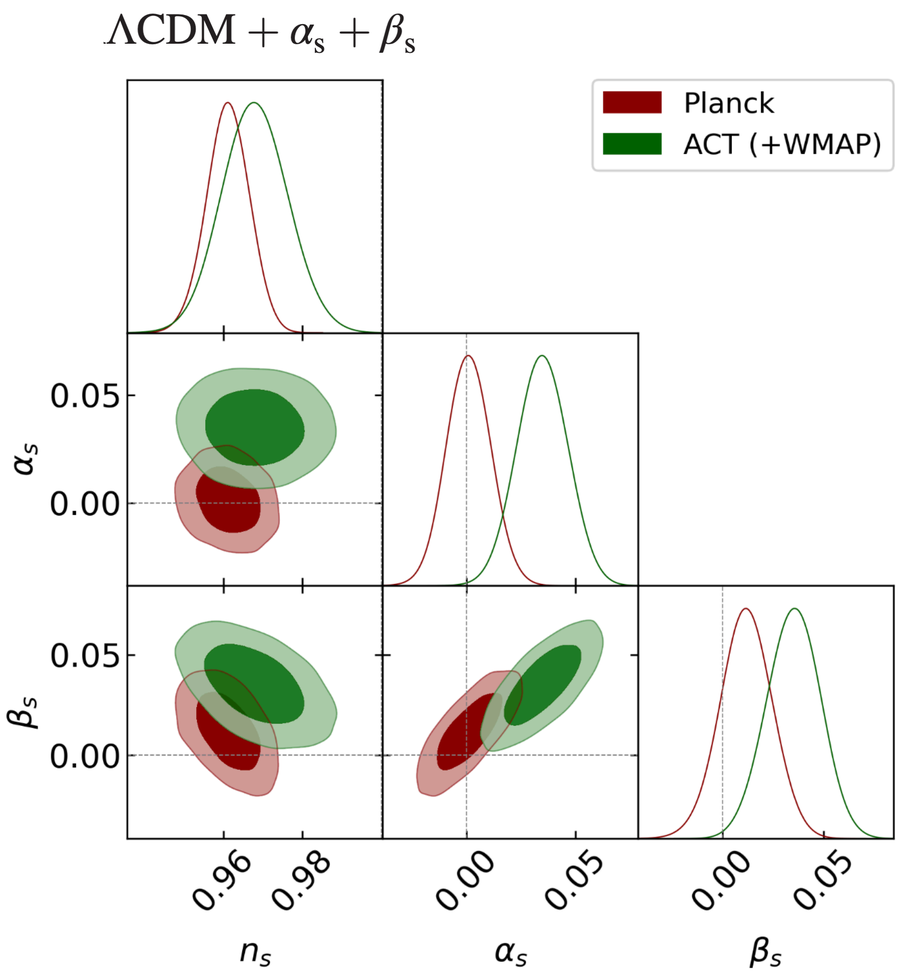
Dark Energy



Dark Energy EOS (w)

- The different CMB data poorly constrain the Dark Energy Equation of state in extended parameter-spaces and, because of the large error-bars, the results are typically consistent with a cosmological constant
- Combining the CMB data with BAO measurements the constraints usually shrink around w=−1
- considering Pantheon in combination with the CMB data, from Planck and ACT we observe a mild preference for phantom Dark Energy ($w < -1$) at a statistical level ranging between 1.5σ and 2.5σ

Inflation



Running(s) of the spectral index

- In the vast majority of the models analyzed the results remain consistent with a vanishing running
- This suggests that the ACT preference for a positive running can be easily recast in different cosmological parameters
- However focusing only on inflationary extensions and including also the running of the running, the ACT preference for a tilted spectrum become very strong (3σ)

Conclusions and outlook

The situation is quite intriguing and not completely clear

- Planck data prefer a closed universe, ACT and SPT (+WMAP) don't
- ACT (+ WMAP) data prefer massive neutrinos, Planck and SPT (+WMAP) don't
- ACT (+ WMAP) data prefer less radiation w.r.t. the SM, Planck and SPT (+WMAP) are in great agreement with N_{eff} =3.04
- ACT (+ WMAP) and Planck both prefers Phantom DE when combined with Pantheon
- ACT (+ WMAP) prefers a positive running(s) of the spectral index in some models (but not in others), Planck and SPT don't

Different CMB experiments are in moderate disagreement also in extended models (2-3 σ)

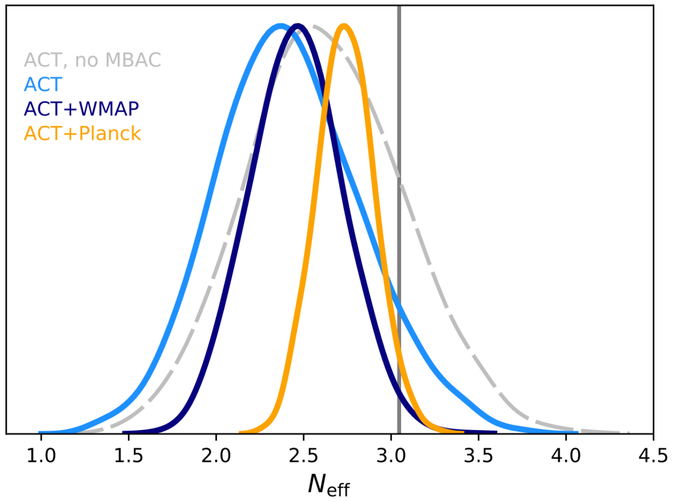
Observational systematics or new physics beyond ΛCDM?

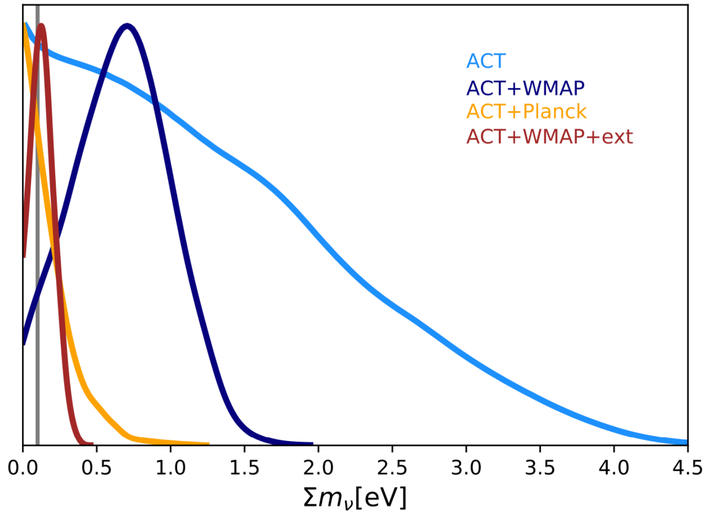
Our analysis is not conclusive, but it reveals intriguing hints that need further investigations and more precise CMB measurements form next-gen experiments may help

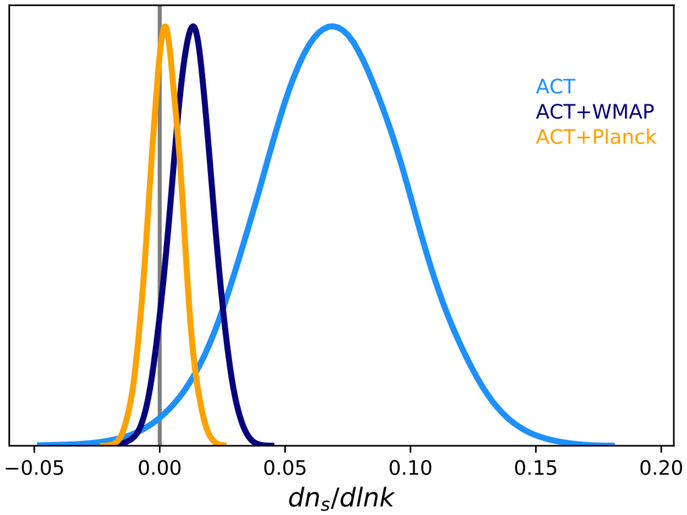
Thank you for the attention

Backup Slides

ACT Anomalies in ΛCDM

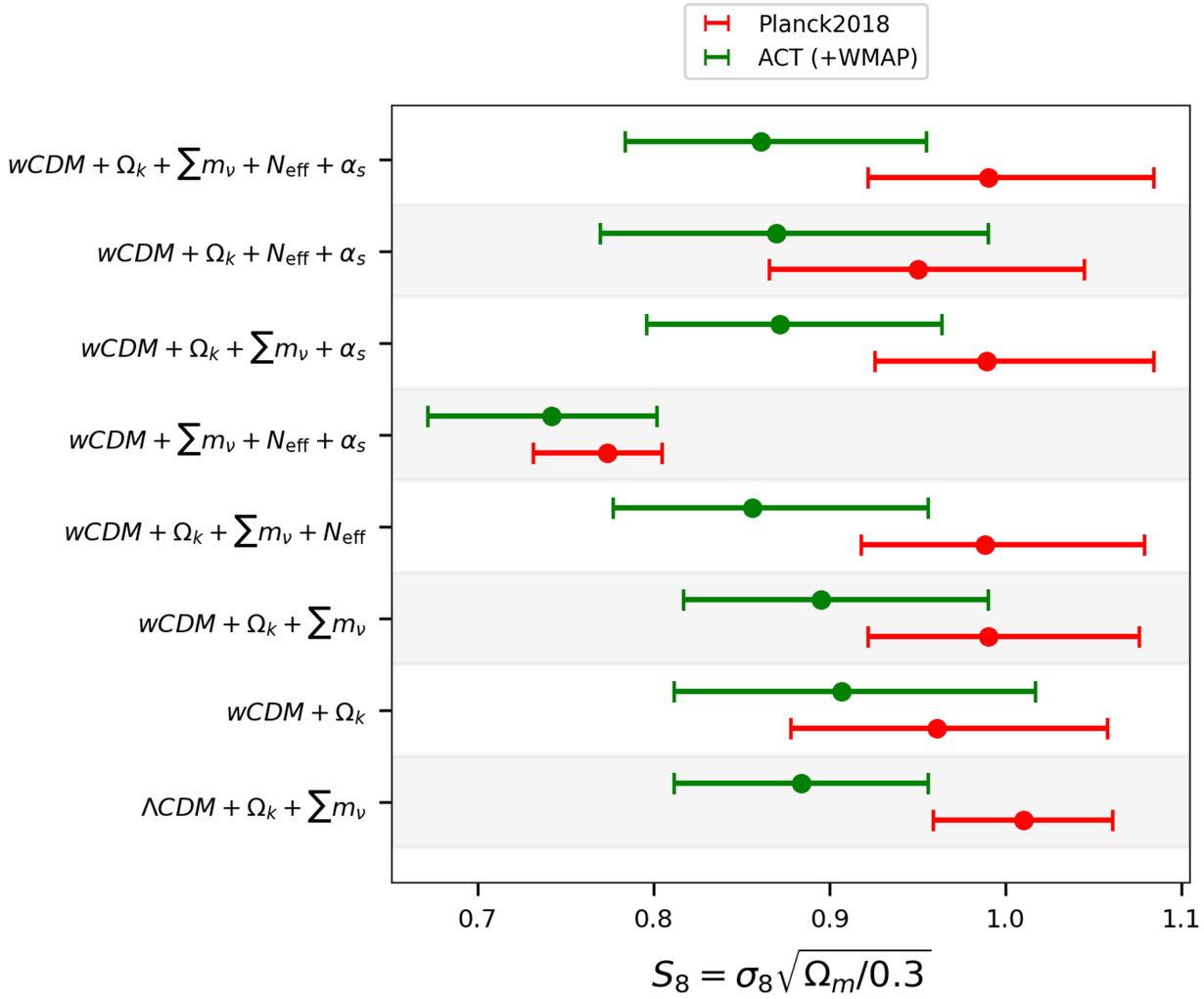






Simone Aiola *et al* JCAP12(2020)047

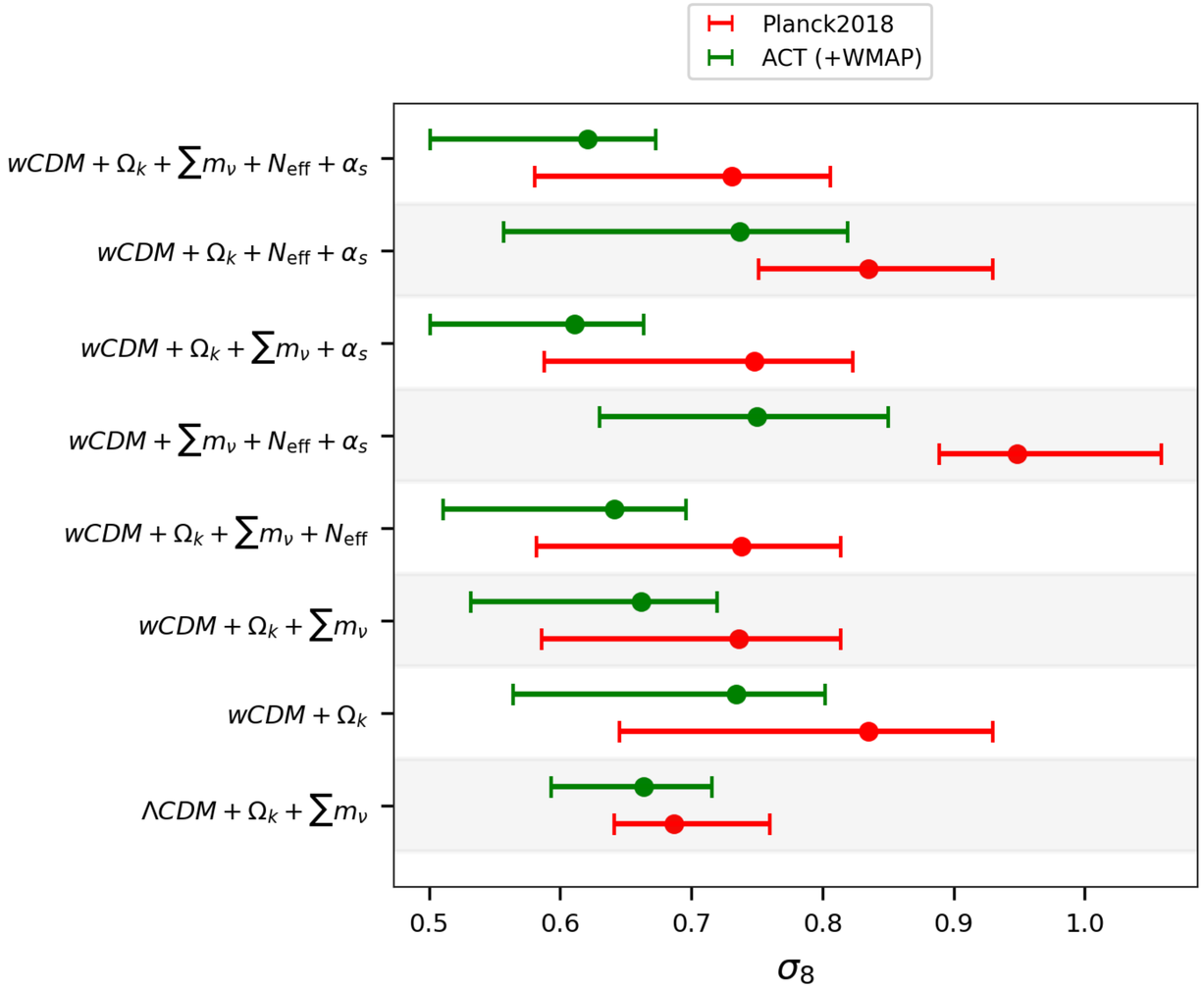
Matter Clustering parameters



Matter clustering (S_8)

- The Planck data show a systematic preference for $S_8 \gtrsim 0.9$, in disagreement with cosmic shear surveys
- This preference is only partially supported by the Atacama Cosmology Telescope and South pole Telescope data that, for many models, suggest instead $S_8 \sim 0.7 - 0.8$, in line with cosmic shear measurements.

Matter Clustering parameters



Matter density (Ω_m and σ_8)

However different values of S_8 often recast discordant behaviors for the parameter σ_8 and the matter density Ω_m

- Ω_m is very badly constrained in extended cosmologies and we observe a shift towards higher values from all the CMB data.
- This shift is usually compensated by a preference for smaller σ_8 in ACT and SPT, but not in Planck.
- Including BAO and Pantheon measurements, we instead recover familiar values $\Omega_m \sim 0.3$ and thus smaller S_8

GLOBAL CONSISTENCY BETWEEN EXPERIMENTS